

### The Montana State University NASA Space Grant Explorer-1 Science Reflight Commemorative Mission

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**Abstract.** Montana State University's Space Science and Engineering Laboratory (SSEL) under support from the Montana NASA Space Grant Consortium is engaged in an earth orbiting satellite student project that will carry a reproduction, using current-day technology, of the scientific payload flown on the United States' first satellite, Explorer-1, February 1, 1958. The Montana EaRth Orbiting Pico Explorer (MEROPE) will carry a single Geiger counter into a 600 km, sun-synchronous polar orbit to measure the corpuscular radiation that characterizes the Van Allen Radiation Belts, first measured by Professor James Van Allen's group with Explorer-1. In contrast to Explorer-1's 14 kg mass, MEROPE, a CubeSat-class satellite, will have a total mass of 1 kg in a cubic volume of 1 liter. The payload will be operated primarily during transits of the earth's radiation belts, where the instrument will also detect the higher energy portion of the electron spectrum responsible for the production of the Aurora Borealis. This paper describes MEROPE's scientific objectives and the miniature Geiger Tube payload designed to carry out those objectives as well as the student designed and built MEROPE satellite bus and project management. An introduction to the CubeSat program and a discussion of their future uses is included.

#### Introduction

The CubeSat concept is a program conceived by Professor Robert Twiggs of Stanford University's Space Systems Development Laboratory to expose students to all aspects of satellite design, manufacture and operation.<sup>1</sup> Ideally intended for university master's degree programs, CubeSats are planned to go from design through construction and testing of a finished product within approximately a one-year timeline. The design constraints of the CubeSat concept limit the total satellite mass to 1 kg and the total volume to 1 liter within a 10 cm cube.

One Stop Satellite Solutions of Ogden, Utah, has arranged a launch for 18 individual CubeSats as a secondary payload aboard a Russian Dnepr rocket (converted SS-18 Inter-Continental Ballistic Missile), with a launch window now slated to open in May, 2002. Launch will be from Baikonur Cosmodrome in Kazakhstan. Various universities and private entities across the United

States and the world are constructing these satellites.

The Montana EaRth-Orbiting Pico Explorer (MEROPE) is the Montana Space Grant Consortium's (MSGC) CubeSat program, being built by the Space Science and Engineering Laboratory (SSEL) at Montana State University in Bozeman. MEROPE will also be the first satellite ever built in Montana. The project is entirely student run, with faculty members acting as advisers. First and foremost, MEROPE is an educational project. Students are involved with every part of the satellite, including but not limited to: designing the satellite, constructing the onboard experiment and all subsystems, fabricating a ground station to control and communicate with the satellite, testing the engineering and flight models, and contributing to public outreach and web site development. MEROPE is being constructed on a low-cost budget of less than \$50,000, including launch, by using mostly off-the-shelf hardware.

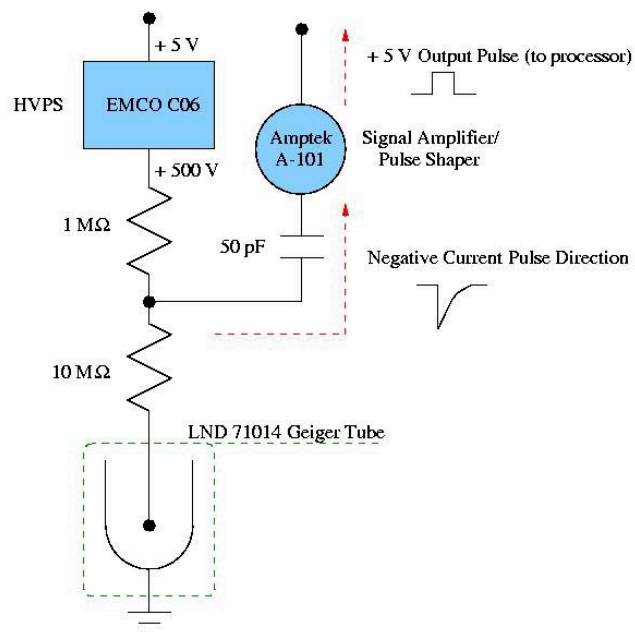
In the first section of this paper, the scientific objectives of MEROPE are described in detail, including the selected Geiger tube, payload circuit, and expected data. A brief introduction to the Van Allen Radiation Belts is provided. The second section explains the systems engineering and project management. Each required subsystem needed to accomplish the mission is also described. Finally, potential future uses, strengths, and advantages of CubeSat-class satellites in space science experiments are discussed.

### Scientific Objectives

MEROPE's mission is to measure the radiation of the Van Allen radiation belts, first discovered by Explorer-1 under the direction of Professor James Van Allen's group of the State University of Iowa (now The University of Iowa). The target mission lifetime is 4 months in orbit.

The Van Allen radiation belts consist of two bands of radiation extending a few hundred km to 65,000 km above the Earth's atmosphere. The inner layer is made of protons left by the decay of cosmic ray induced albedo from the atmosphere. The outer layer is dominated by electrons that are produced by injection and energization events following geomagnetic storms.<sup>2</sup> These particles become constrained along Earth's magnetic field lines, executing gyro-motion about them. As the magnetic field strength increases near the Earth's magnetic poles, this perpendicular velocity grows in magnitude while the radius of motion decreases. Consequentially, electrons will reach a point where their velocity along the field line reaches zero and the particle reverses direction, only to reflect again near the other magnetic pole. These points of reflection are known as *mirror points*. Electrons become effectively "trapped" in this manner along the field lines. By pointing a radiation detector perpendicular to the magnetic field these trapped electrons can be counted and measured.

The payload designed to accomplish these measurements includes a Geiger tube manufactured by LND, Inc., and its supporting hardware (Figure 1). The LND 71014 is lightweight (about 6 grams total mass), low volume (7.62 mm long with an 8.7 mm maximum diameter), and robust enough to measure the radiation flux expected within our orbit. The tube consists of a 446 stainless steel cathode casing electrically insulated from the anode wire, which extends into the ionization chamber. The ionization chamber is filled with Neon gas and sealed with an Indian Mica window about 1.5 mg/cm<sup>2</sup> thick. The window end of the tube will be mated to an aluminum collimator whose purpose is twofold. First, it will provide a sheath to conveniently mount the Geiger tube to MEROPE's internal power printed circuit board (PCB). Second, it will reduce the tube's field of view to roughly  $\pi/12$  steradians (sr) and diminish the effective window diameter to close to a millimeter, for an overall geometric factor of roughly .002 cm<sup>2</sup> - sr. This design attempts to insure that the tube will never achieve a particle count rate of 40 kHz,



**Figure 1. Payload Circuit Diagram.**

beyond which the tube will saturate.

Using a standard energy-loss rate graph where the density of the window is  $2.82 \text{ g/cm}^3$ , electrons of  $\sim 50 \text{ keV}$  and greater are expected to have sufficient energies to enter through the mica window into the ionization chamber. Once inside, the electrons will ionize enclosed neon atoms. By maintaining the anode at  $+500\text{V}$  and the cathode at ground, the ions can be separated and accelerated. The ionized electrons acquire enough energy to ionize gas atoms that they collide with producing more electrons, which likewise ionize other atoms and the process continues. This production of secondary ionizations is called a *Townsend avalanche*. The avalanche of charge spreads out along the detector and produces a large output pulse, independent of the incident particle energy, which is sent to a pulse-shaping microchip to be prepared for counting by MEROPE's central processing unit.<sup>3</sup>

For the payload High Voltage Power Supply (HVPS), an EMCO C06 capable of high voltage, low current output was chosen. Ideally, the Geiger tube needs to be sustained at  $+500 \text{ V}$ , so the EMCO HVPS will be used for testing the payload circuit only. The actual MEROPE launch will use a more stable, space-rated HVPS from Southwest Research Institute. The charge sensitive preamplifier-discriminator selected is the A-101 from AmpTek, Inc. The A-101 accepts a negative pulse and converts it to a shaped,  $5 \text{ V}$  square pulse which will then be counted by the onboard processor.

Collimator design involves knowing the expected electron flux within our orbit. Our analysis has relied mainly on data from the Space Environment Monitor (SEM-2) onboard the NOAA Polar Orbiting Environmental Satellite (POES). POES orbits in an  $800 \text{ km}$  sun-synchronous orbit. Using their baseline and extreme flux data allows a geometric factor to be selected that keeps the Geiger tube from reaching saturation. It also gives a reference for what our data is expected to resemble (Figure 2).

Electron flux through the mica window is

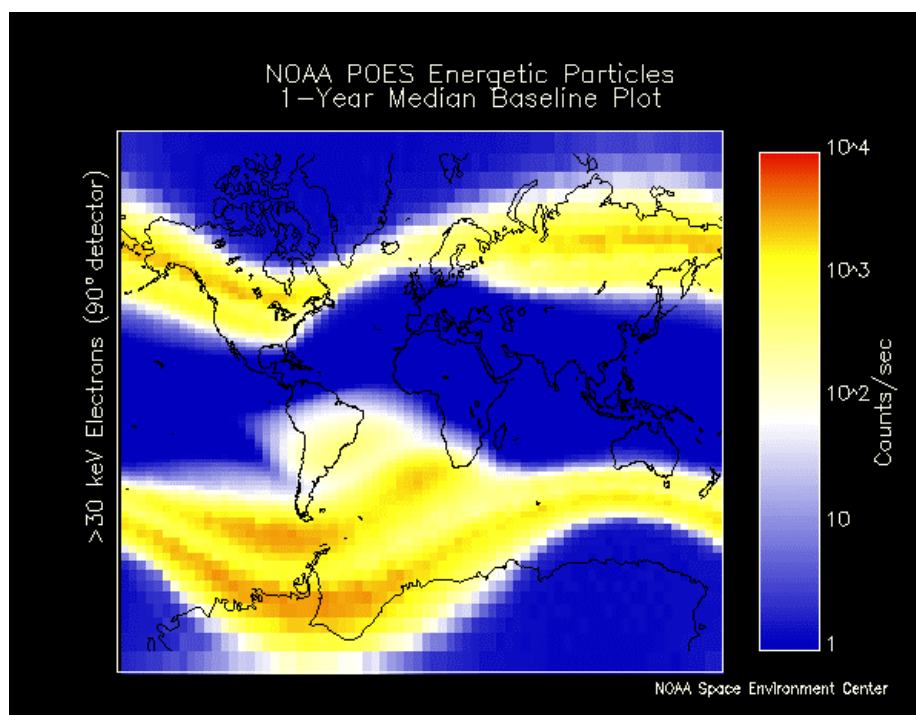


Figure 2. NOAA POES Energetic Particles count rate.

not the only flux that needs to take into account. Other facts which must be considered include: 1) high energy electrons ( $\sim 300 \text{ keV}$ ) can penetrate the satellite sidewall, tunnel through the Geiger tube casing and enter the ionization chamber, 2) protons entering the tube through the window ( $\sim 400 \text{ keV}$ ) or through the satellite ( $> 10 \text{ MeV}$ ) will trigger the detector identically to an electron, and 3) X-rays of cosmic, solar, or terrestrial origin or

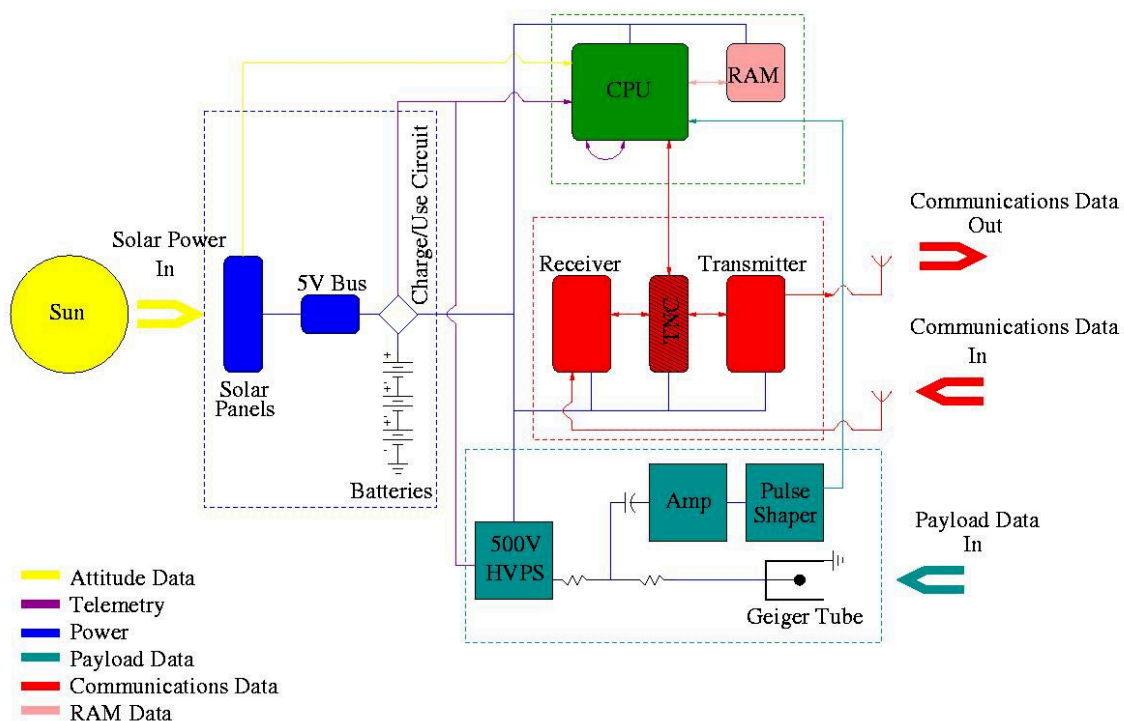
bremsstrahlung will trigger the detector. Fortunately, higher energy particles (both protons and electrons) should be rare enough that they will merely require a small correction in our data analysis. The effect of X-ray triggering is still being studied.

### Subsystems and Systems Engineering

The goal of having a completely operational self-sustaining satellite dictates the obligatory subsystems needed to complete this task. Locating and building subsystems that will be consistent with the design constraints of 1 kg total mass and 1 liter total cubic volume creates an interesting engineering and managerial challenge, demanding the selection of the lightest and smallest components available. Adding to the difficulty of this project is the short timeline, relative to conventional satellite missions. The MEROPE project design phase was initiated in

January 2001 with the goal of completion by July 23<sup>rd</sup> of this year.

Over fifty undergraduate students in majors ranging from all types of engineering to business management and graphic design volunteered to learn and work on the MEROPE project. They were split into "design phase" teams by interest, which included the Payload, Firmware, Thermal Control, and Business teams, with four independent Structure/Power/Communications design teams. In March of 2001 a Preliminary Design Review (PDR) was held wherein the four concepts were narrowed down and combined into two blueprints to be built: the primary satellite and a backup. To begin construction, students were then reorganized into the ten specific subsystem teams described in this section and a payload team with the tasks explained above. These systems interact as shown in our systems engineering diagram (Figure 3).



**Figure 3. MEROPE Systems Engineering Diagram.**

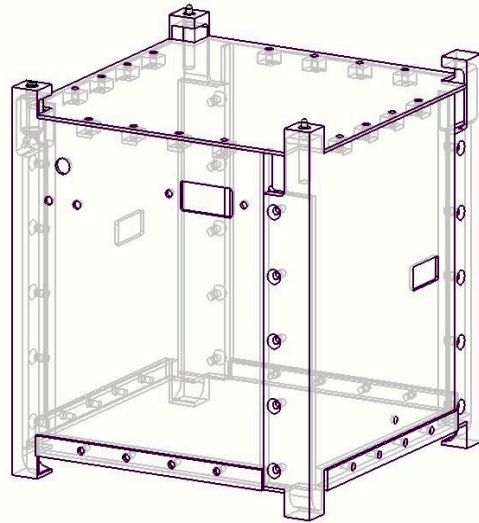
## Structure

The California Polytechnic State University, who is fabricating the Poly Picosatellite Orbital Deployer (P-POD) launch system, dictates the structure of MEROPE on a primary level in order to perform with the P-POD. Thus, the goals of the MEROPE Structure subsystem include development and/or fabrication of the chassis, mechanical switches (e.g. power kill switch), and separation spring mechanism as specified along with MEROPE's antenna deployment system and card retainer selection and placement as outlined in PDR. The structure must withstand the specific g-loads, acoustic and vibrational loads, and thermal effects stipulated.<sup>4</sup> Another environmental criterion, which must be considered in the development of these systems, is outgassing of materials. All materials have met the low-outgassing requirement enumerated in NASA Reference Publication 1124.<sup>5</sup>

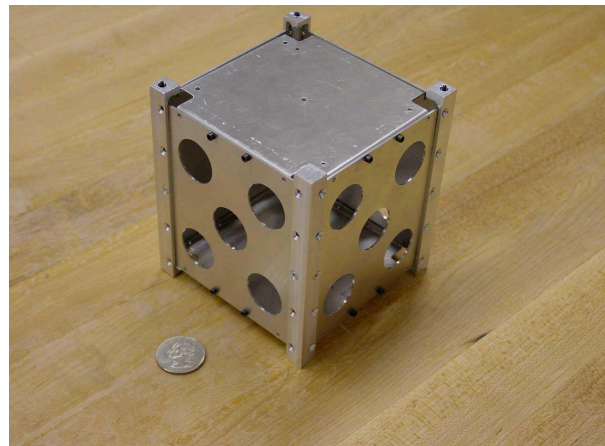
The chassis of MEROPE consists of machined 6061 or 7075 aluminum sides fastened together with countersunk screws and locknuts. Launch rails must be incorporated into the design to successfully interface with the P-POD. The estimated final mass of the chassis and fasteners is 220 g. Two models are currently being worked on: (1) a primary model whose launch rails are integrated into each adjacent side wall, built using a computer-controlled mill (Figure 4), and (2) a backup model simply constructed of 6 flat sides attached with fasteners to the individual launch rails (Figure 5).

The antenna deployment system consists of a crescent-shaped plastic housing where the antenna is attached, curled up and kept in place by a nylon string. After launch, current will be sent through a resistor attached to the nylon causing it to melt and the antenna to unfurl out the side of the satellite into space.

Three PCB's are needed to carry the MEROPE subsystems: a Firmware board for the onboard computer processor and RAM, a Power board carrying the batteries, power circuits,



**Figure 4. MEROPE Primary structure model.** Holes on the front side exist for the pull-before-flight pin, and serial port computer interface. Holes on the right side include the payload collimator (bottom center) and antenna deployment mechanism (rectangular cutout on both right and left side).



**Figure 5. MEROPE Backup structure model.**

attitude control, and payload, and a Communications board carrying the antennas and transceiver. Card retainers will be fastened parallel to the CubeSat rails, allowing easy removal of each board for servicing.

### ***Power***

MEROPE must be functional for the mission lifetime of 4 months, which cannot be achieved within our design constraints by batteries alone. The power system devised for MEROPE therefore utilizes both solar panels and rechargeable Lithium-Ion batteries.

The solar panels are triple junction GaAs solar cells, produced by EMCORE. They feature high efficiency (23%) and will be custom made to 37 mm by 76 mm, allowing two on each side of the satellite. On average, each side will be capable of generating 1.68 W of power. The maximum power that can be generated, up to 5.81 W, occurs when more than one side is facing the sun and the others collect Earthshine and albedo.

The battery design is based around a 1200 mAh 3.7 V Lithium-Ion battery from Polystor Corporation. The power system design has the advantage of having a variable-power charging chip that will dump excess power generated into the battery. This saves waste heat and virtually guarantees the satellite will stay near full charge in all orbits.

### ***Firmware***

The computer hardware (firmware) aboard MEROPE has the task of controlling most aspects of the internal electronics: communications uplinks and downlinks, communications between satellite systems, and organizing payload and telemetry data for transfer to the ground station.

This subsystem is centered on a Motorola MC68HC812A4 (HC12) microcontroller. This model was chosen for its speed, processing power, and intrinsic features such as: eight built-in analog to digital converters, two sets of serial interfaces,

and multiple interrupts for both software and hardware. This chip was supplied complete on a prototype board by the Seattle Robotics Society.

For RAM we are using a 150 kbytes Integrated Device Technology CMOS Supersync FIFO IDT72291. This memory was chosen because of its convenient physical size and capacity, and for the FIFO (First-In First-Out) design, which eases the programming and interface significantly.

The system is written to use a main loop that is as small as possible; in this case the main loop consists of listening to the receiver and checking if the state of the battery needs to be changed (i.e. start/stop charging). This loop is then interrupted to do the various other routines that need to be done, which include: payload, attitude, telemetry, writing external RAM, system clock, and computer-operating-properly (COP) routines. The advantage of this is the modularity of the system allows future missions to add interrupt routines (ISR's) without modification of the main loop.

Telemetry, attitude, and payload data must share the 150 kbytes of memory available. The bitstream, or data stream, of MEROPE has been set up to maximize the available stored data that will fit into our memory allocation. The system has been broken up into three different data sets: telemetry, attitude, and payload.

1. The telemetry data set is the "housekeeping" information of the satellite. This consists of battery temperature, battery voltage, battery charge state, processor temperature, bus voltage, bus current, and high voltage. This information is collected every 60 seconds on orbit. This data is stored in a given order for decoding on the ground. The stored information consists of all the values and the time at which the values were collected. To get this time we record "Hard Time Stamps" (HTS) which are the absolute mission elapsed time (MET) and "Soft Time Stamps" (STS), which are the least significant two bytes of the

3 byte system clock, effectively giving the time since the last HTS. Stamps occurring at regular intervals negates the need to collect soft time stamp times, since the HTS time interval is known.

2. The attitude data set indicates which sides of the satellite are in the Sun at any given time by indicating which solar cells are receiving power. This information will be used to evaluate the attitude control system and for fine-tuning the communications system of future missions to maximize the transmission power from the satellite. This, like the telemetry, stores the HTS or STS for each data point.
3. The payload set is the data collected from the Geiger tube. The tube output signal is converted to a TTL level logic high pulse for every ionizing event. The processor then counts these pulses. After every N counts the processor writes a time stamp into memory. Since the number of counts per stamp, N, is fixed, this system permits the processor to merely record the time at which the data occurred, and not the data itself. Therefore, the experiment will record more accurate data in high-flux regions, since the resolution will increase. In less interesting, low-flux regions, the resolution will decrease and less data will be taken, giving an approximate duty cycle of 50% and ultimately saving memory space. It is a balancing act between the payload and other systems for memory space.

### ***Communications***

The Communications subsystem hardware consists of a standard Paccomm Pico-packet terminal node controller (TNC) with 128 kbytes of cache memory and a Yaesu VX-1R dual-band handheld transceiver with 1 W RF output. Both TNC and radio operate off of a 6 V-DC power supply input. The baud rate default is 1200 bps, with the capability (and bandwidth) to expand to 2400 or 9600 bps. The communications system will relay the processor's serial data stream to the

ground through an amateur (HAM) radio link. Uplink to MEROPE is at a frequency of 145.835 MHz (VHF, 2 m radio band) with 20 kHz bandwidth, while the downlink is at 437.445 MHz (UHF, 70 cm band).

The only uplink command MEROPE will accept is an encrypted "send data" command from the ground station, instructing the processor to key the TNC and radio transmitter. Once MEROPE receives this command, it uses the AX.25 packet protocol to perform a 128 kbyte memory dump. The entire serial stream will be less than 128 kbytes in size, and can be cached in the TNC's memory for packetization and transmission. Both the radio and TNC will be "on" in "standby" mode, until keyed by the processor to begin transmission. This command and data flow has the advantages of being simple, robust, and reliable.

The antenna consists of a half-wave dipole with two separate elements on opposing sides of the spacecraft. A single dipole will be used for both 2 m reception and 70 cm transmission.

### ***Ground Station***

A ground station located at Montana State University will handle operations and communications with the satellite. Due to MEROPE's output power being less than one watt, our antenna selection will be very critical. The most promising possibility is a pair of omnidirectional circular ("eggbeater") style antennas, where neither steering nor rotation are required. Due to free space attenuation, our signal will be quite weak upon reaching the station. Therefore, we will be implementing a preamp to enhance our signal by 20-25 dB before it is run into our TNC unit.

The location of our antenna array is also an issue, due to our location in Montana's Gallatin Valley. We require a spot with a clear view, unimpaired by both the mountains and campus buildings.

## ***Software***

The computer software being written for the ground station is responsible for encoding and decoding transmissions to and from MEROPE. To initiate communication, an encrypted command is sent to MEROPE directing it to begin transmitting. The transmitted data will be in an order that the software is programmed to understand and decode. The software is constantly checking for errors. Any bits in the data set that are astray or do not conform to the proper ordering will not be decoded.

The Software subsystem team is also programming a Graphical User Interface (GUI) that will use the attitude telemetry data to create a near-real time computer simulation of MEROPE's orientation in space. The goal of this GUI is to keep a visual record of attitude for our experiment and for future projects.

## ***Thermal Control***

The Thermal subsystem on the MEROPE project is responsible for monitoring and ensuring a safe thermal environment that the satellite will experience throughout its orbit. The term "safe thermal environment" means that all components of MEROPE are within their optimal operating temperatures. Any significant variance from any of the component operating temperatures could result in a failure of the satellite mission.

For the mission to succeed, the satellite must survive the rigors of the brutal space environment where temperatures range from 120 C (248 F) in the sunlight to -100 C (-212 F) in the Earth's shadow.<sup>6</sup> Not only do the temperatures in space themselves induce a burden upon the satellite, but the rapid fluctuations of these temperatures can also cause problems for the satellite. Unfortunately, MEROPE cannot operate properly within this temperature range, and thus its thermal environment must be controlled.

MEROPE will be launched into a polar, sun-synchronous orbit, which means that the

satellite will pass over the Earth at approximately the same local solar time each day. Since the local time of the orbit plane is dictated by the primary payload and will not be known until a few months before launch, the satellite may experience anywhere from 50% to 100% sun exposure for one full orbit. When exposed to the sun, the satellite will receive three types of solar loads: direct solar, reflected direct solar (albedo), and Earthshine. Direct solar is the direct infrared radiation from the sun and is by far the most significant solar input that the satellite will receive. Albedo is the direct solar infrared radiation that is reflected off of the Earth's surface. While only being 35% as intense as direct solar, it is a significant solar input since our orbit is relatively low. Earthshine is the weak and usually negligible infrared radiation that is emitted from the Earth. When in the eclipse of the orbit, the satellite will not receive any external heat loads and must rely solely upon internal heat during this time.

Considering the size, dimensions, internal heat dissipation, and MEROPE budget, the thermal team will utilize a passive thermal control system, which does not utilize power or any type of working fluid in order to control the temperature of the spacecraft, as opposed to an active thermal control system. Advantage must be taken of internal heat conduction and body-mounted radiators in order to control the amount of heat that exists on MEROPE. The first item to focus upon in a passive thermal subsystem design is how the operating temperature ranges of each of the components compare to the temperature extremes that are expected for the satellite. The thermal team has calculated that the satellite would operate between 65 C (149 F) and -35 C (-95 F) without any type of thermal protection.

The next stage of the thermal subsystem design is to begin to analyze in detail the many conduction and radiation paths that exist on MEROPE. Calculating the environmental solar loads and internal heat generation must also accompany this analysis. Once all of the heat transfer paths are quantified and catalogued and the various heat loads are computed, the team can

then begin to calculate the estimated temperatures for all components of MEROPE at different times of the orbit. Designing for a worst-case hot condition of 100% sun exposure and a worst-case cold condition of less than 50% sun-exposure, the Thermal team will then assess the need for thermal protection. If a certain component must be thermally isolated, (this would be done if it is deemed that the satellite as a whole will not operate within a given component's operating temperature range), multi-layered thermal insulation, thermal tape, and various other thermal stand-offs will be used in order to maintain the component's temperature within its given temperature range. The radiator area that is needed in order to maintain the satellite at the given temperature limits requires the determination of the type of surface finish that the outer and inner structure must have, optimizing the efficiency of the radiator. Upon implementing the proper thermal protection for MEROPE, new temperatures for all components throughout the orbit will be computed. These values will be the temperatures that we will expect during the flight of MEROPE. Thermistors will be placed on all vital components to monitor and compare their temperature readings to those that were calculated for the final thermal subsystem design.

While MEROPE is in flight, the thermal team is responsible for monitoring the thermistor readings and fine-tuning the system based upon gathered data. Another task for the thermal team after launch is to observe any problem areas of the thermal subsystem during flight and make adjustments for Montana's next pico satellite.

### ***Attitude Control***

Considering that MEROPE will be inserted into orbit without stability about any axis, which hinders communications abilities and mostly nullifies the Geiger tube experiment, some form of attitude control is required. Opting for passive attitude control over heavy, complicated gyroscopes or electromagnets, MEROPE will employ permanent magnets and iron core damping rods to align itself with the Earth's magnetic field.

Knowing the mass and volume of each component that will launch aboard MEROPE, we are using a computer model to calculate the satellite's center of mass and moment of inertia. This will indicate specifically the magnet strength needed to orient MEROPE in orbit.

The magnets will experience torques about the magnetic field lines according to Equation 1, where  $\mu$  is the magnetic moment of the rods and  $B$  is the Earth's magnetic field,

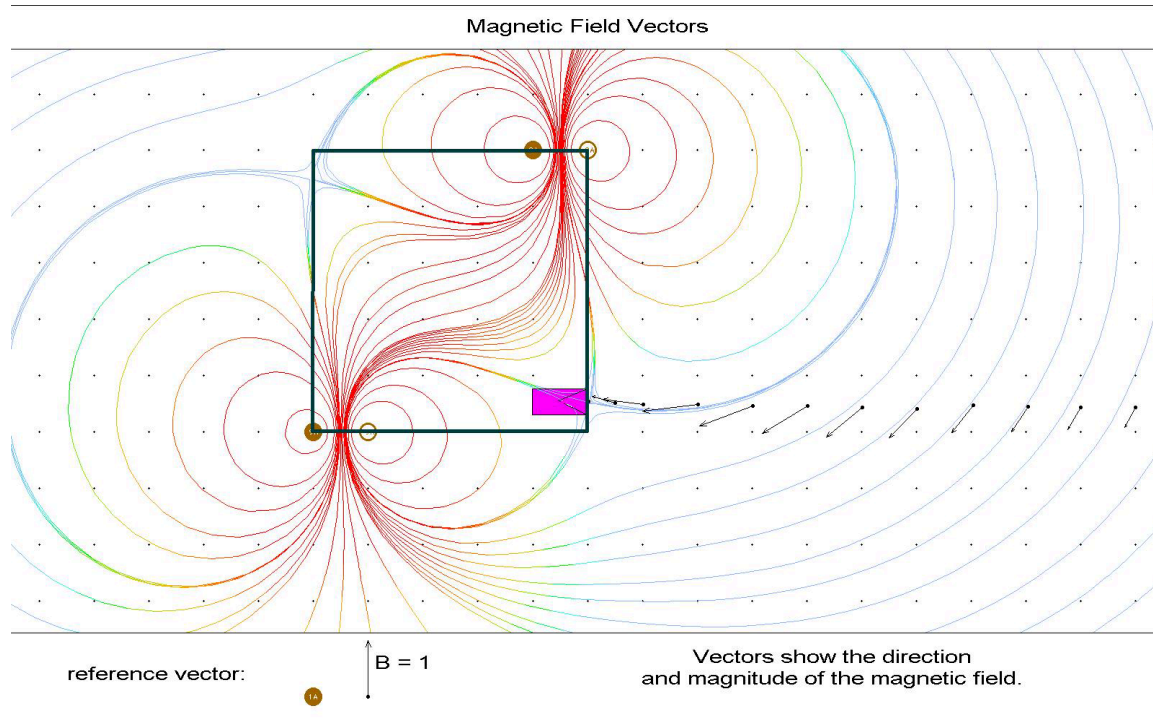
$$\tau = \mu \times B \quad (1)$$

causing the satellite to librate. This libration will be minimized using the damping rods, which will be attached inside MEROPE perpendicular to the magnetic field lines. The rods will experience hysteresis as the satellite swings off the magnetic axis, converting this motion into thermal energy and eventually dissipating the oscillations altogether. This system is based on the attitude control of the Munin nanosatellite.<sup>7</sup>

An interesting consequence of passive magnetic attitude control is its interaction with our Geiger tube payload. Preliminary calculations show that the magnets required for stabilization create a relatively strong magnetic field in the region surrounding MEROPE (~ 1 G). This may have the detrimental effect of routing electrons into or away from our payload window, tainting our data. To avoid this problem, simulations have been performed that show the effect can be minimized by placing the magnets in opposite corners of the satellite and the payload in another corner (forming a triangle coplanar with the power board). Instead of being directed towards or away from the collimator, electrons on a path to intercept the Geiger tube will simply remain on that path (Figure 6).

### ***Integration and Testing***

The Integration and Test subsystem team is responsible for interacting with every subsystem to ensure that each is adequately tested and able to



**Figure 6. Magnetic field from MEROPE passive magnetic attitude control. The Geiger tube is shown in purple.**

synthesize with the other systems. Testing will include complete thermal vacuum chamber cycling and vibration tests performed at qualification levels on engineering prototypes, and at workmanship levels for the flight unit.

The thermal vacuum test will be used to compare and verify the expected temperatures of MEROPE and its components, as specified by the Thermal Control subsystem team. This analysis is performed in an oxygen-free chamber that is subject to cyclic hot and cold conditions that are designed to simulate the actual orbit that the satellite must endure. If temperature readings vary too greatly from expected values, or if the engineering prototype fails in any way thermally, the thermal subsystem must be reworked or partially redesigned. Once the prototype passes a thermal vacuum test, the satellite is thermally ready for its actual flight.

The vibration analysis is executed on a "shake table" that is programmed to oscillate

according to the vibrations and harmonics of the actual Dnepr rocket thrust. When the model completes a shake test successfully, it is ready to withstand launch.

Due to the short timeline of the project, each subsystem is being constructed first on a prototype board where it can undergo bench testing with the other systems it must mate with. For instance, the payload must be successfully operated by the power prototype board and send the required voltage pulses to the processor before it will be placed on a PCB. This approach should minimize problems during final integration.

A flight test will also be performed in which an engineering model is attached to a high-altitude balloon, part of the Montana State University BOREALIS (Balloon Outreach, Research, Exploration And Landscape Imaging System) project.<sup>8</sup> The CubeSat, using a larger pancake style Geiger tube, will be sent to 90,000 feet where the instrument will measure cosmic

rays and the data will be transmitted to the ground, testing the payload, firmware, and communications subsystems.

### ***Business***

The Business subsystem handles logistics for the satellite project such as budgets, schedules, and public outreach. Public outreach has included several informational talks to the public, travelling presentations to secondary schools throughout Montana, and a website: <http://www.ssel.montana.edu/merope>. Another program that has been initiated is entitled "Send Your Name to Space" in which anyone can complete a form on our website to have their name and a short message burned to a compact disk which will be carried into orbit aboard MEROPE. Educating the public is an important aspect of our project.

### **Future Uses**

CubeSats have the potential of accomplishing assignments that would be impossible for typical satellites to perform by themselves. Satellites of this class have the potential to lead to low-cost constellations of spacecraft making coordinated measurements of the highly dynamic and spatially structured space environment. While key tradeoffs between resource needs and resource availability (e.g. power, telemetry, mass, volume, and cost) constrain payload sophistication, the tremendous advantages of having even simple dispersed

multipoint measurements of the Geospace environment far outweigh the loss of payload sophistication in many instances.

CubeSats can also be used as an economical test-bed for space-rating new technologies. The quick construction time and status as a small, lightweight secondary payload should allow testing of space components much faster than using conventional satellites.

The simple value of using CubeSats to train future leaders and workers in the aerospace industry cannot be overlooked. The CubeSat project is a nearly ideal educational endeavor, making satellite design and construction reasonably affordable for a much broader range of institutions.

### **Conclusion**

The Montana Earth Orbiting Pico Explorer will launch from Kazakhstan in May of 2002 carrying into orbit a student designed and built reproduction of the payload aboard the United State's first satellite, Explorer-1. The design constraints of 1 kg total mass and 1 liter total volume lead to an ambitious and challenging project ideal for training students in the rigors of aerospace engineering. In time, hopefully uses for CubeSats will be found making them as common and in demand as the much larger and more expensive designs in use today.

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**Mike Obland** - Earned his B.A. in Physics and Mathematics in 2000 from the University of Montana. Currently he is a Ph.D student in physics at Montana State University. He is the Deputy Project Manager as well as the Payload and Business/Outreach subsystems lead. In his few moments of spare time, he enjoys outdoor activities including exercising, camping, and fishing.

**George Hunyadi** - Earned his B.S. in Physics at Montana State University (1997). Worked a total of one year at NASA's Goddard (Greenbelt, MD) and Marshall (Huntsville, AL) Space Flight Centers as staff and research associate for the NASA Academy. Currently pursuing M.S. in Electrical Engineering at MSU, with an emphasis in RF and Communications systems. George is Project Manager as well as the Communications, Telemetry & Data Handling (C,T & DH) subsystem lead. He enjoys amateur astronomy, skiing, climbing, and fishing.

**Stephen Jepsen** - Earned his B.S. in Geology and Physics from California State Univ, Fresno to then move to graduate work at Montana State University. Steve is the lead on mechanical & structure and is in charge of operations. He spends his winters telemark skiing and summers hiking/fishing. Steve also spends a lot of time reading.

**Brian Larsen** - Earned his B.S. in Physics and Mathematics in 2000 from Linfield College and is now a graduate student at Montana State University. He is trying (successfully?) to balance his duties as software and integration & testing lead and his need to ski and bike.

**Dr. David Klumpar** - David Klumpar is a research professor and director of the SSEL lab here at Montana State. He received his B.A. in physics and mathematics at University of Iowa. He received his M.S. in physics from the University of Iowa in 1968. In 1972 he received his Ph.D in physics from the University of New Hampshire.

**Dr. Charles Kankelborg** - Charles Kankelborg Received his PhD in Physics from Stanford University in 1996. He is currently an Assistant Professor of Physics at Montana State University, working on the MOSES spectrometer project. Drawing on his background in rocket and satellite instrumentation, he helps to advise the MEROPE student leaders. He enjoys spending time with his family and studying the history of Christianity.

**Dr. William Hiscock** - Bill Hiscock is a Professor of Physics at Montana State University and is also Director of the Montana Space Grant Consortium and the Montana NASA EPSCoR Program. He received his B.S. in physics from the California Institute of Technology in 1973. He received his M.S. (1975) and Ph.D. (1979) in physics from the University of Maryland. He enjoys hiking, biking, and flying.

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<sup>1</sup> See <http://ssdl.stanford.edu/cubesat/index.html>.

<sup>2</sup> Schulz, M. and Lanzerotti, L. J., Particle Diffusion in the Radiation Belts, Volume 7 of Physics and Chemistry in Space, Springer-Verlag, New York, Heidelberg, Berlin, 1974.

<sup>3</sup> Krane, K.S., Introductory Nuclear Physics, John Wiley, 1988.

<sup>4</sup> See <http://ssdl.stanford.edu/cubesat/design.html>.

<sup>5</sup> NASA Reference Publication 1124, <http://epims.gsfc.nasa.gov/og/>, June 25, 2001.

<sup>6</sup> <http://quest.arc.nasa.gov/space/teachers/suited/3outer.html>, June 25, 2001.

<sup>7</sup> [http://munin.irf.se/frames/index\\_main.html](http://munin.irf.se/frames/index_main.html), June 25, 2001.

<sup>8</sup> See <http://www.physics.montana.edu/borealis/>.